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14. ABSTRACT

Research on state-of-the-art conductor forms of Coated Conductors made from the superconducting material, $YBa_2Cu_3O_x$, has been performed. The principal results obtained are: 1. Misoriented substrate grains control the critical current performance of today's good conductor prototypes; 2. Magneto-optical imaging is a good means of studying the current flow barriers in such conductors; 3. Low angle grain boundary properties are of great importance to the percolation of current through a polycrystalline coated conductor; 4. Buffer layer microstructures control the way that epitaxy is built up from substrate to $YBa_2Cu_3O_x$ overlayer. The work has been carried out in collaboration with groups at AFRL, ORNL and industry.

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Fundamental Studies for High Temperature Superconductor Conductor Technology

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OBJECTIVES

Developing high critical current density (J_c) in conductors is the most essential step to developing attractive power technologies from high temperature superconductors (HTS). HTS materials possess attractively high J_c values over a large domain of temperature and field but real conductors contain many defects that limit the transport current density below their very high local values. Our goal is to understand the current limiting mechanisms of actual and prototype HTS conductor forms. Two generations of conductor form are discussed today, a first generation based on $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$, which is available now in kilometer lengths, and a second generation conductor based on biaxially aligned $YBa_2Cu_3O_{7-\delta}$, which has received a proof of principle in short lengths. Intense effort is being applied to scaling up YBCO coated conductors from cm to meter lengths. The central focus of our work is to understand the different roles that flux pinning and connectivity and thus microstructure play in determining the J_c of YBCO conductor forms. Our major effort is to use coordinated studies of the voltage-current characteristics, magneto optical imaging and microstructural analysis to reveal where current limiting defects reside. This integrated view is then used to raise the properties of the whole conductor.

Collaboration is an essential component of our work. Some samples we make ourselves but a vital part of our work is that we receive samples from many leading groups. Our work is guided by our strong linkages with the leading groups in the field at American Superconductor Corp. (ASC), ORNL, LANL, and the AFRL. An important link to the AFRL groups of Tim Peterson and Paul Barnes and Chuck Oberly was developed in 1999. It developed out of wider collaborations within the Coated Conductor Development Group (CCDG), an industry-led working group that meets periodically to discuss key issues associated with Coated Conductor technology. The general thrusts of our effort support central thrusts of the New World Vistas Program.

SUMMARY OF WORK COMPLETED

The global thrusts of the work are to understand the ultimate critical current potential of YBCO in coated conductor form. To this end we have performed the following work under this contract:

1. Studies of current limiting mechanisms in Coated Conductor samples.
2. Studies of the microstructure of buffer and YBCO layers of Coated Conductors.
3. Analysis of the influence of obstructions to current flow and their influence on local dissipation.
4. Studies of grain boundaries in bicrystals.
5. Facility development.

*1. **Current limiting mechanisms*** (CLM) in coated conductors have been studied primarily by Magneto optical (MO) imaging coupled with Electron Backscatter Kikuchi Pattern (EBKP) analysis [1,3,4,7]. This work has been collaborative, being performed on AFRL, ORNL and LANL samples. The most dramatic results have been obtained on AFRL samples, on which it has been possible to directly correlate the observed MO granularity to the grain structure of the YBCO, which is itself determined by misoriented grains in the underlying Ni. The critical angle for the misorientation was in process of being finally determined at contract end (it was found to be 4°). These results are of great value for all CC samples because the granular flux patterns are common to all samples of RABiTS or deformation textured substrates that we have seen from both national laboratory and industry sources. Our results have 3 important consequences:

a. The headroom in 1 MA/cm^2 samples is high since such samples exhibit many barriers. In fact qualitatively similar results are obtained on 2.5 MA/cm^2 samples, making it clear that there is significant headroom in the CC system.
b. The fact that there is a threshold of 4° in AFRL, all-PLD samples is consistent with the fact that bicrystal films grown at UW [8,9] and elsewhere exhibit the start of current-limiting in the range of 4-7° in pure [001] tilt boundaries. In principle, we might expect similar variability from CC sample to CC sample because it appears from bicrystal studies that small and not well understood processing changes provoke changes in both grain and grain boundary properties from one sample to another that are not yet well understood.
c. The best texture reported for biaxially aligned Ni substrates lies in the range of 7-10° FWHM, as measured by x-ray pole figures. These values clearly imply that there will be Ni grains (with their YBCO epitaxial overlayers) that are misoriented beyond the point at which their GBs start to become obstacles to current flow.

2. ***Studies of the microstructure of buffer and YBCO overlayers:*** We studied the use of Y_2O_3 as a buffer on Ni [2,10,11] during the visit of Dr Ataru Ichinose from CRIEPI, Japan. He produced single buffer layers of Y_2O_3 on textured Ni by electron-beam evaporation of Y metal in a weakly oxidizing environment. Y_2O_3 has been used by several groups as a cap layer on top of YSZ but the desirable nature of Y_2O_3 as a single buffer (it contains no elements foreign to $YBa_2Cu_3O_x$) has received little explicit study. One of the key problems that we observed is the extreme sensitivity of the subsequent $YBa_2Cu_3O_x$overcoat to any porosity in the buffer. As soon as the oxygen pressure was raised to deposit YBCO by PLD, local eruptions of NiO through the Y_2O_3 were observed. This produced extremely granular MO images. Some control of the Y_2O_3 porosity was developed by controlling the partial pressure of O_2 during oxidation of the Y, but the problem was never fully resolved. Extensive studies were also made of various buffer layer combinations made at ORNL, in this case all of 3-layer buffer combinations [3,4,11].

3. ***Analysis of the influence of obstructions to current flow and their influence on local dissipation***: Studies of the MO response of a variety of CC samples made by LANL, ORNL and industry during the period 1997-1999 led to a growing conviction that current flow is percolative in high quality CC prototypes, even as in BSCCO composites. This qualitative judgement, based on both IBAD- [1,3] and DETEX-variants of CC, requires more quantitative definition. Starting in mid-1999 through samples supplied by the Peterson-Barnes-Oberly groups at AFRL, we have been able to start this work. Using all-PLD CeO_2/Y_2O_3–stabilized ZrO_2/CeO_2 (CYC) buffers overlain with $YBa_2Cu_3O_x$, the AFRL groups were able to make CC samples on DETEX-Ni with J_c(0T, 77K) >1 MA/cm^2 [1]. These samples exhibited a clearly granular image of flux penetration, the scale of penetration being ~50 μm. Direct correlation of the YBCO to the buffer and to the underlying Ni substructure showed that their granular MO structure was entirely linked to Ni grain boundaries, but also that not all Ni GBs appeared. Measurement of the grain-to-grain misorientation by Electron Backscatter Kikuchi Pattern (EBKP) analysis showed that the threshold for appearance of a GB in the MO image was sharp. Below 4° none were visible, while above 4° all were visible, though to differing extents. The work engendered a lively debate, particularly at ORNL and led to the sending of their very highest J_c samples made yet, over 2.3 MA/cm^2. Study of these was just commencing at end of contract. Qualitatively speaking, the results on the ORNL samples appear identical to those obtained on the AFRL samples. The influence of obstructions to current flow on the local dissipation was studied analytically [5,14]. It was seen that the local dissipation is highly non-linear with defect length for a non-ohmic conductor, where $V=kI^n$, where n is 20-30. This raises many possibilities, amongst them that the shape of the V-I curves for most HTS are far from intrinsic and determined by their current-obstructing defect populations. We plan experimental tests of this in our new contract.

4. ***Bicrystal studies:*** Bicrystal studies have been carried out primarily under NSF support during the first term of the MRSEC, but their results provide considerable motivation for our CC studies because of their focus on low angle GBs of the type seen in CC. Two bicrystal

results [9] in particular motivate our CC researches. The first is the great variability of the ratio of the grain boundary critical current density, J_b, to the grain critical current density, J_c, i.e. J_b/J_c observed by Heinig et al. [xx] for 5-7° [001] tilt GBs made on $SrTiO_3$ substrates. The second is the possibility of modifying the grain boundary transparency by doping carriers into the GB, the first proof of which were given in early 1999 at the University of Augsburg.

5. ***Facility Development***: With an equipment supplement awarded in late 1999, we were able to add considerably to the capabilities for coated conductor research in Madison. Major effort was put into upgrading the laser ablation system that we use for YBCO deposition. We replaced an old Questek 2720 purchased in 1991 whose repetition rate was a maximum of 25Hz at a maximum energy of 450mJ with a new Lambda Physik LPX210I laser that has a repetition rate of up to 100Hz and an energy of up to 700mJ. The gas handling of the new laser is much simpler and safer too. This system will be installed in early Spring 2000. We also ordered a variable temperature, gas-flow cooled scanning tunneling microscope from Oxford Instruments. This system will enable us to study vortex properties at GBs and to make local voltage measurements around GBs and near defects so as to test the predictions of Gurevich and Friesen [5] concerning the influence of defects on local dissipation and current flow. This facility is cost-shared with Professor Mark Rzchowski in Physics. We also plan to add transport capability at the nanovolt level to the MO facility in early 2000 in order to complement the induced current characterization that is possible presently by magneto optics.

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